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Program for the Feasibility of Developing a High Pressure Acoustic Levitator

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FEASIBILITY OF DEVELOPING A HIGH PRESSURE
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FOREWORD

This paper is the result of a contract that was awarded to study the feasibility of developing a high pressure acoustic levitator (HPAL). The work was conducted by a research staff at Intersonics, Incorporated, Northbrook, Illinois. The principal investigator was Dr. Charles A. Rey. Dennis R. Merkley was project manager, and Gregory R. Hammarlund was chief electrical engineer. Also involved in the study were Thomas Danley, Daniel Benedict, Deborah Rogers and Betty Armstrong. The contract monitor at NASA Lewis Research Center was Dennis S. Fox.

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PROGRAM FOR THE FEASIBILITY OF
DEVELOPING A HIGH PRESSURE ACOUSTIC LEVITATOR

FINAL REPORT

1. SUMMARY

This program is directed toward an effort on the part of Intersonics to determine the feasibility of developing a High Pressure Acoustic Levitator facility for use in the Microgravity Materials Science Laboratory at the Lewis Research Center. Such a facility would allow small samples to be levitated without a container and processed at high temperatures in an inert or oxidizing atmosphere. Using this facility would allow preliminary work to be conducted in an earth-bound laboratory prior to sending experiments into the microgravity of space.

In evaluating the feasibility of developing a pressure levitation system, the approach taken was to make some preliminary measurements using the Medium Pressure Acoustic Levitator available at Intersonics, Incorporated.

Since the acoustic restoring forces are known to decrease with increasing gas temperature because of a number of factors - most, but not all of which are well understood - it was necessary to measure the acoustic field intensities and the corresponding acoustic levitation forces as a function of temperature and absolute gas pressure. Additionally, measurements of other quantities and effects, such as furnace cavities, size and material, specimen size and density, and effects of acoustic cooling were studied. All of these results were then employed in determining the expected capabilities obtainable in the design of the High Pressure Levitation System.

This report provides a summary of the laboratory study, the conclusions and their effect on the overall design of the pressure facility. Finally, this report presents the overall design concept for a High Pressure Acoustic Levitation facility, including conceptual designs for all of the subsystems, along with the relevant drawings and schematics supporting that design.

2. INTRODUCTION

Results from tests utilizing the Intersonics Medium Pressure Acoustic Levitator have revealed several specific benefits arising from processing with increased gas pressure. These benefits demonstrate the feasibility of meeting the requirements of a containerless materials processing facility to be utilized in a 1-g environment. The advantages observed include enhanced acoustic coupling of the sound source into the gas, higher obtainable Sound Pressure Levels (SPL), reduced harmonic content in the acoustic field, and extended sound source life. Increasing the pressure of the gas significantly improves the capabilities of acoustic levitation in the 1-g environment for processing of denser specimens at higher temperatures.

Enhanced acoustic coupling is the result of improving the match of acoustic impedance between the radiator and the gas. As the pressure of the gas is increased, the acoustic impedance of the gas increases in the direction of that of the driver. Better energy transfer occurs with this improving impedance match producing a more efficient system. Therefore, for the same electrical input power, higher SPL's can be reached as the pressure of the gas increases.

Harmonics present within a sound field can cause deformation to the shape of the energy well. The formation of energy wells occurs through the interference of an acoustic wave and its reflected wave. This interference creates

a pattern of energy wells located at every half wavelength. If harmonics were superimposed, a distortion of the energy well results, with pressure anti-nodes occurring in the center of the energy well. Typically these harmonics are generated by the inherent shocking up effect of the gas at high sound intensities. This harmonic distortion increases as the sound intensity increases due to the non-linearity of the gas. Spectrum analysis shows a reduction in the harmonic content in the acoustic field when the pressure of the gas is increased. Reducing the harmonic content aids in producing well defined and deeper energy wells. These better defined, spherically shaped energy wells help promote stable acoustic levitation.

Another factor is that the useful life of a flexural radiator increases with increasing pressure. This increased gas pressure allows higher SPL's to be produced for a given radiator excursion. Therefore, a radiator can be operated at a safe level while producing higher sound intensities than could be obtained at 1 atmosphere. Reduced stresses on the transducer material will thereby lengthen the materials' useful life.

In addition to the benefits which became apparent in the testing, a number of adverse effects of pressurization were identified. Substantially increased amounts of power are required to maintain high temperatures in a furnace being operated at high pressures. This increase in required power has two main contributors. With increased pressure the higher gas density increases the heat carried away by gas convection mechanisms which are enhanced in an unsealed furnace. In addition, the convective flow is increased due to the larger pressure differentials created by the increased gas density. These mechanisms also serve to increase the effective thermal conductivity of porous fiber insulation. Convection has an additional effect on the specimen through

a mechanism known as acoustic cooling. These effects can adversely affect specimen stability, and also prevent the specimen from fully reaching the furnace hot zone temperature.

Consideration has been given to these and other relevant areas in the proposed design of a High Pressure Acoustic Levitation System. A description of the design will follow a discussion of some of the most significant data collected.

3. RESULTS AND DISCUSSION

Although a considerable amount of data was collected from the testing and applied to the system design, only a small portion will be presented in this report. The data which is presented here is that which most significantly bears on the ability to accomplish the design goals of the system.

3.1 Furnace Power Requirements

The curves shown in Fig. 1 represent the power required to heat the test furnace to 900, 1200, and 1500° C, and its dependence on increases in pressure. The furnace used for this test is a different configuration than the proposed design and is subject to a considerable amount of convective heat loss, and other losses due to the heating element configuration. Also, this data does not reflect acoustic cooling effects which would add significantly to these power requirements because of increased convective effects. Due to the sealed nature of the proposed furnace design, the power requirements expected for this proposed furnace will be somewhat less than that of the test furnace. In addition, acoustic cooling effects should be reduced in the new design due to the sealed nature of the furnace.

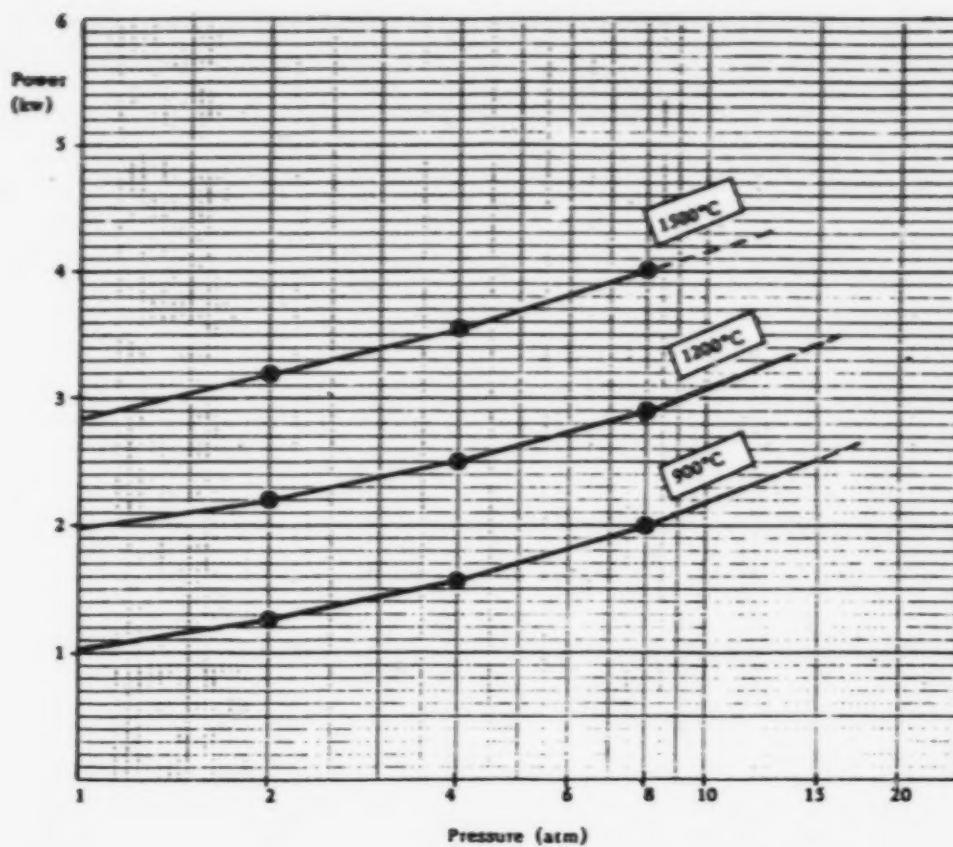


Fig. 1 FURNACE POWER vs SYSTEM PRESSURE

3.2 Sound Pressure Level vs. Pressure

An increase of gas pressure changes the acoustic intensity and Fig. 2 shows graphically the effect of this pressurization on the SPL. The plot shows that for every doubling in atmospheric pressure, a gain of 3 dB in SPL is experienced, provided the input power to the sound source remains constant. This data was obtained by measuring the SPL of a sound source similar to one which will be described in Sec. 4.1 of this report. The gas pressure was increased while a constant input power of 10 Watts was maintained.

3.3 Harmonic Distortion vs. Pressure

Fig. 3 shows the effect on the harmonic content of a sound wave as the gas pressure is increased. It can be seen from this that although the intensity at the fundamental frequency is being maintained at a constant level, the amplitude of the second harmonic, which is the most detrimental to levitation, is decreasing by 3 dB for every doubling in atmospheric pressure. It should be noted, however, that this data represents the effect at only one SPL. The magnitude of this effect may differ at higher SPL's since distortion levels increase rapidly at 1 atmosphere beyond 160 dB.

3.4 Acoustic Levitation Pressure and Temperature Dependence

The curves plotted in Figs. 4 and 5 represent results of test runs performed in the Medium Pressure Facility at Interasonics, Incorporated. Test runs were performed so that the necessary parameters required of a levitation processing facility could be studied. These parameters included acoustic levitation force, temperature and system pressure. For each run, a specimen was injected into the furnace cavity and levitated. The input power was then

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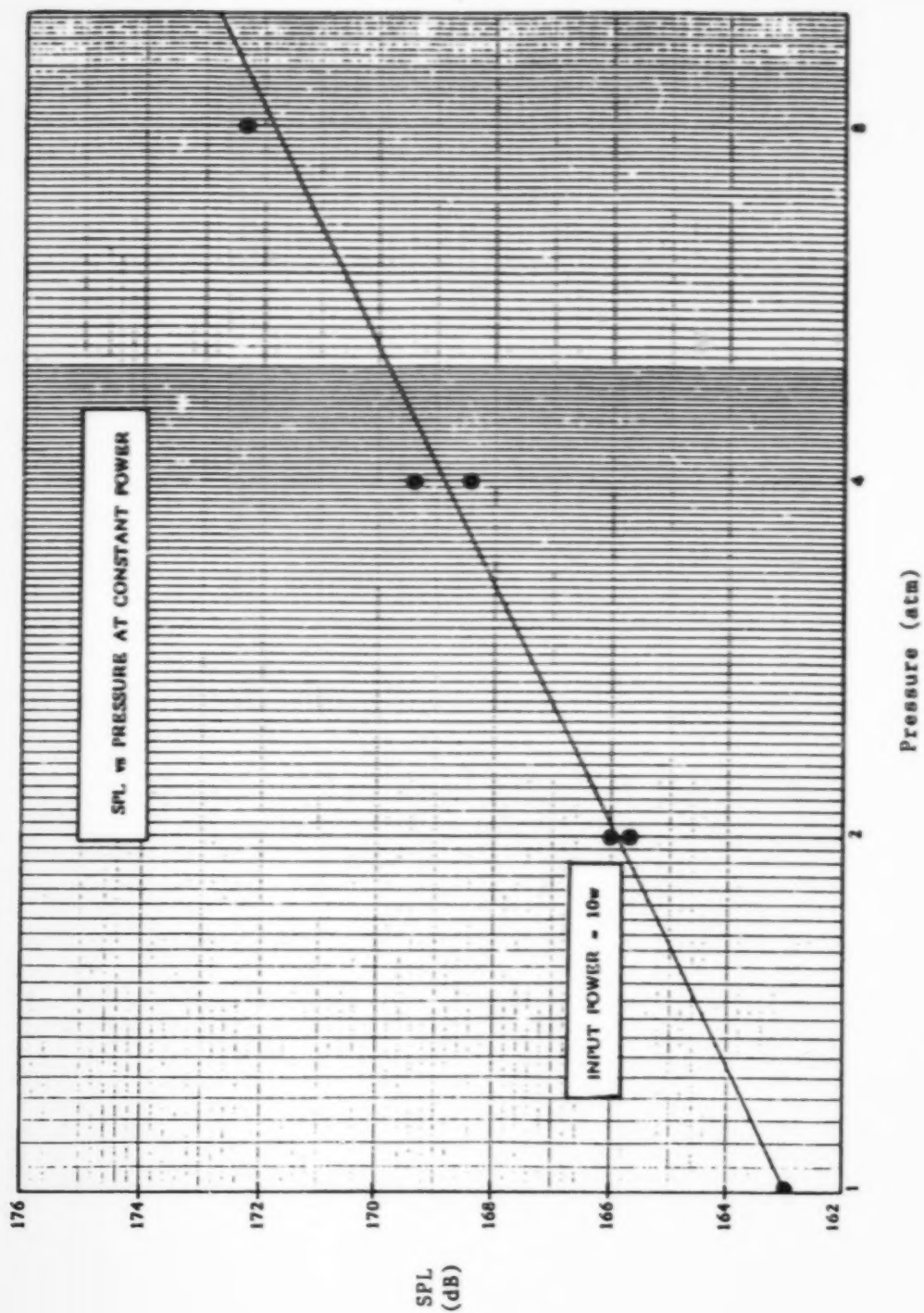


Fig. 2 SPL vs PRESSURE AT CONSTANT FLOW

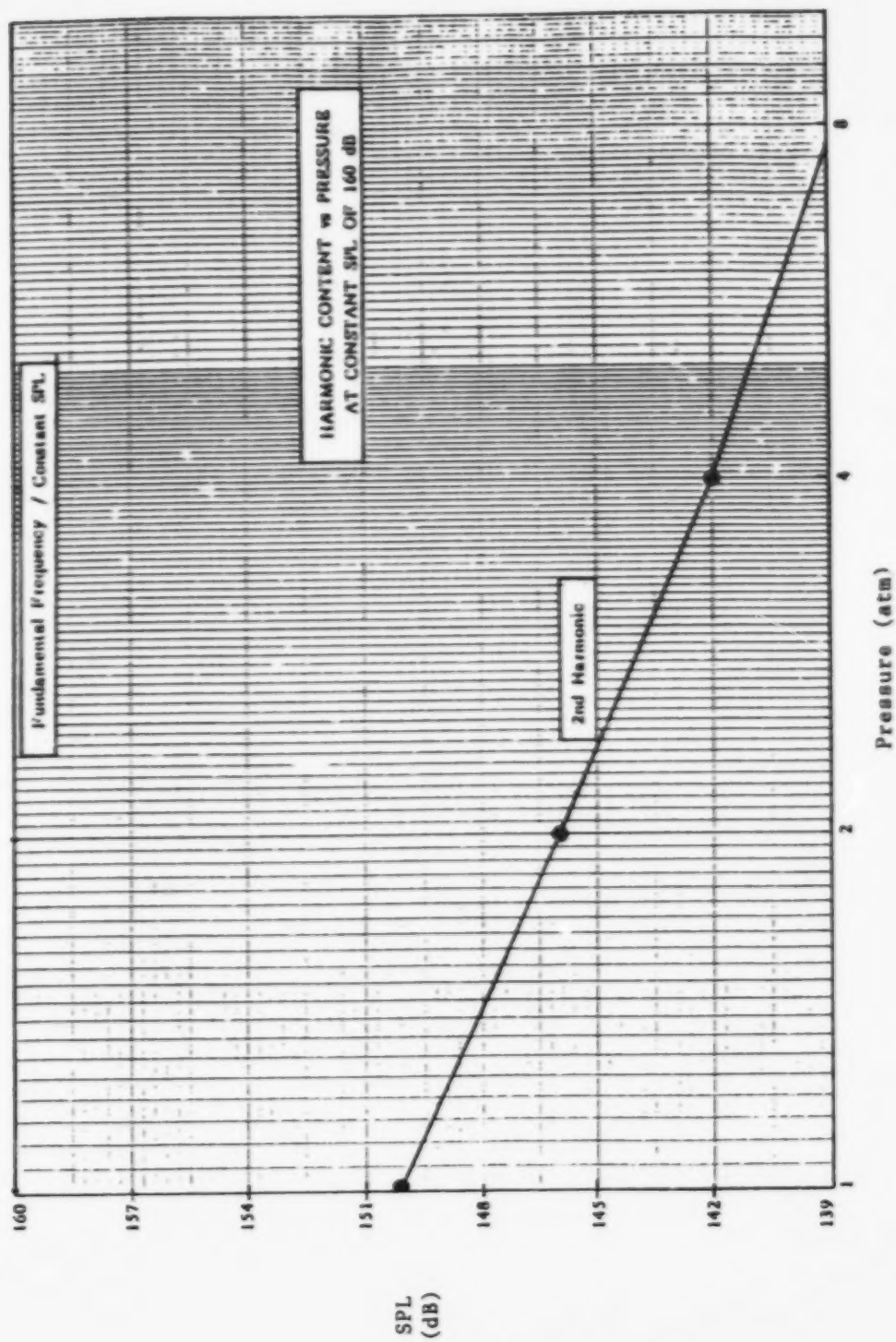


Fig. 3 HARMONIC CONTENT vs PRESSURE AT CONSTANT SPL

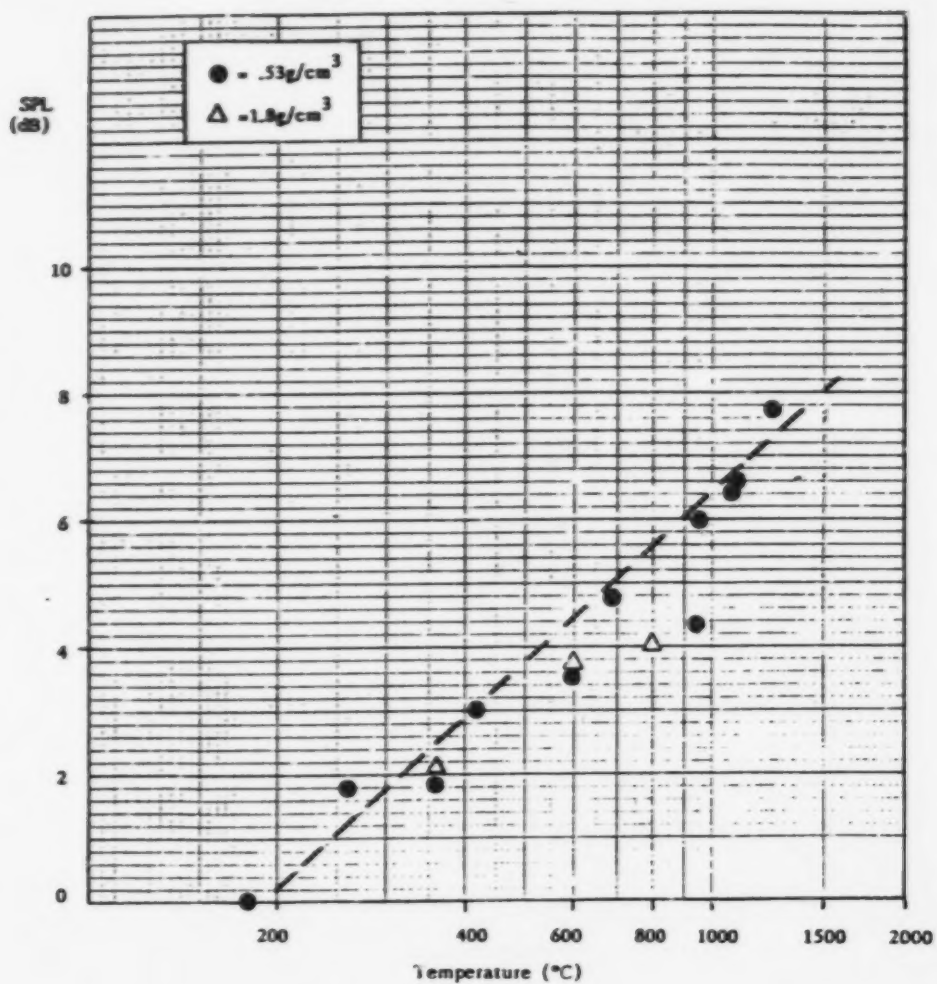


Fig. 4 ACOUSTIC INTENSITY REQUIREMENTS vs TEMPERATURE

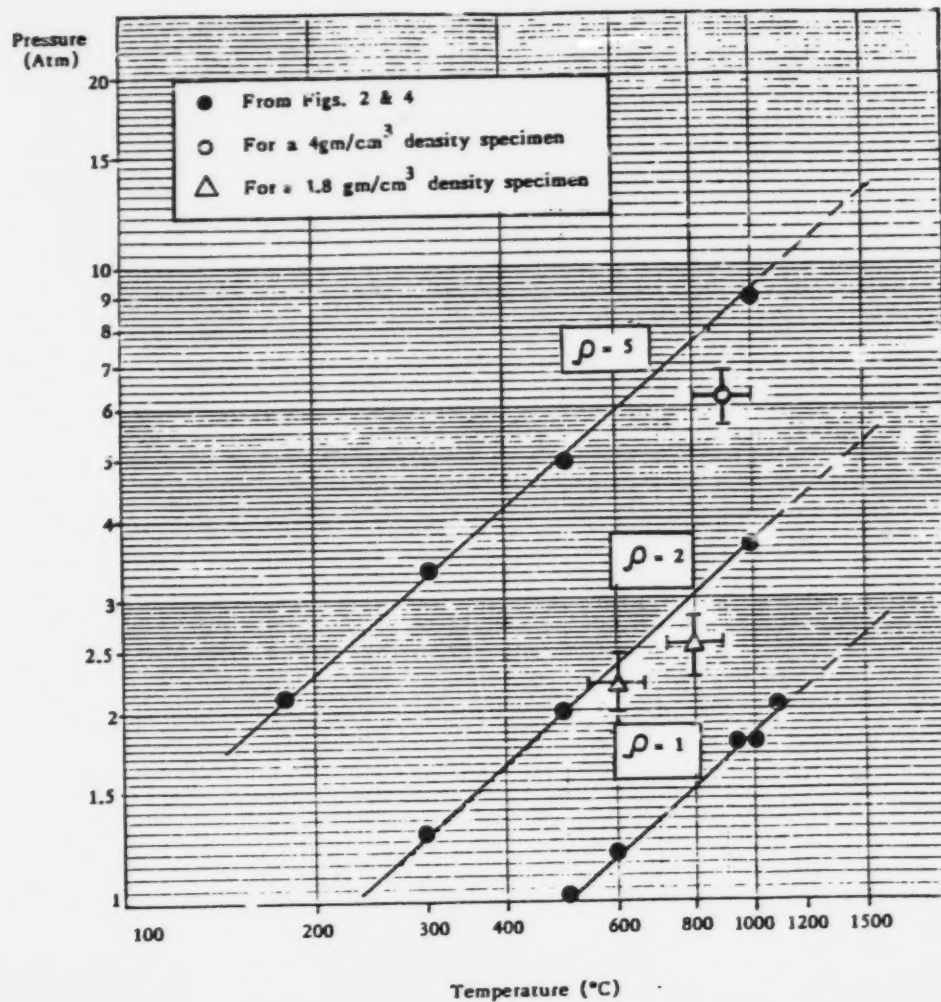


Fig. 5 MINIMUM SYSTEM PRESSURE REQUIRED VS TEMPERATURE

slowly reduced until the specimen just dropped out of the energy well. This minimum input power to the transducer required to levitate the specimen was then recorded. This sequence was performed for several specimen densities at various system pressures for temperatures up to 1300° C. A summary of all the data collected is presented in Fig. 4 and Fig. 5. Fig. 4 is a plot of required SPI to levitate samples of various densities at temperatures up to 1300° C. Extrapolations to 1500° C are presented. In this plot the ordinate represents the required acoustic intensity needed from the transducers in order to maintain levitation at these temperatures. However, since high dB levels cannot be reliably measured in a high temperature furnace, all dB levels have been referenced to the measured output of a standard transducer which was required to levitate a specimen at room temperature at 1 atmosphere (STP). It was found that an intensity of 157 dB was needed to levitate a .53 gm/cm³ sphere at room temperature at 1 atmosphere. This is approximately 7 dB below the 0 dB shown at the origin of Fig. 4. The majority of data plotted is for a density of .53 gm/cm³ with other density specimens normalized to that value. This plot clearly shows the clear relationship between the acoustic intensity required versus gas temperature even for differing specimen densities and system gas pressures. A straight line extrapolation appears to be reasonable, at least to 1500° C.

The plots in Fig. 5 represent the relationship between specimen density and the system pressure required to levitate a specimen of that density at a given temperature. The curves were calculated using the data presented in Fig. 4. First, using the acoustic intensity requirement taken from the ordinates of Fig. 4 as a function of temperature, a normalized intensity was found for

specimen densities of 1, 2, and 5 gm/cm, assuming full input power to a single acoustic transducer. Then, using the curve in Fig. 2, the minimum system pressure was obtained and the results plotted versus temperature. Some data which were obtained directly and independently in a similar test setup are displayed (un-normalized) for comparison. The point near the $\rho = 5$ line is for a 4 gm/cm³ density specimen and the points near the $\rho = 2$ gm/cm³ line are for a 1.8 gm/cm³ specimen. These points are shown with vertical and horizontal error bars. The horizontal bars reflect the uncertainty in specimen temperature due to thermocouple placement while the vertical bars are due to the estimated errors in determining the mean acoustic intensity. These points are quite consistent with the new data. These curves can also be extrapolated easily to 1500° C indicating a minimum pressure requirement of about 14 atmospheres.

4. CONCLUSIONS

Analysis of these significant data areas and all other relevant data has provided a basis for the design of the High Pressure Acoustic Levitator. Fig. 1 shows the need to design a tightly sealed furnace in order to reduce the heater power requirements and to reduce other adverse effects produced by convection. Figs. 2 and 3 show the most significant benefits and the fundamental reasons for the use of pressurization to enhance acoustic levitation. The increase in sound pressure level due to pressurization provides greater levitation force without increasing input power or mechanical stress on the transducer. In addition, the decreased harmonic distortion which occurs with increasing pressure greatly improves the shape of the energy wells thereby improving levitation capability. The combination of these two provides considerably higher SPL's with much lower harmonic distortion than is possible at 1 atmosphere. Using this data in conjunction with the data analysis shown

in Figs. 4 and 5, appropriate processing parameters can be established. The appropriate pressure can be selected for a given specimen density and processing temperature by first determining the SPL required. However, if the SPL requirement is extremely high, then an even higher pressure can be used to reduce the transducer power requirements and the harmonic distortion levels. This data supports the possibility of achieving the goals for this system as well as the viability of the proposed system.

5. GENERAL CONCEPTUAL DESIGN

5.1 Overall Facility Configuration

The High Pressure Acoustic Levitation Facility is shown in Fig. 6. This consists of the main processing unit chamber, and a number of supporting subsystems such as the electronic controls, gas supply and control system, and data monitoring and acquisition components.

The Levitator Processing Unit, as shown in Figs. 7A and 7B, consists primarily of a high pressure chamber, which contains an electrically heated furnace with a number of ports through which acoustic energy can be coupled into the furnace in order to levitate a small specimen at the center of the furnace. There are, in addition, access ports for specimen injection and retrieval, for temperature measurement thermocouple probes, external illumination of the specimen and optical recording of its processing, and, lastly, a gated port in the bottom of the furnace assembly through which the specimen may be dropped before or after being cooled or solidified. If the option of dropping the specimen is chosen, there exists several additional options for recovering the specimen. The specimen can be caught in a small container just below the levitator proper or the specimen could be allowed to fall into a drop tube where it could be cooled very rapidly by radiative losses and by con-

duction to the surrounding gas before being caught at the bottom of the drop tube.

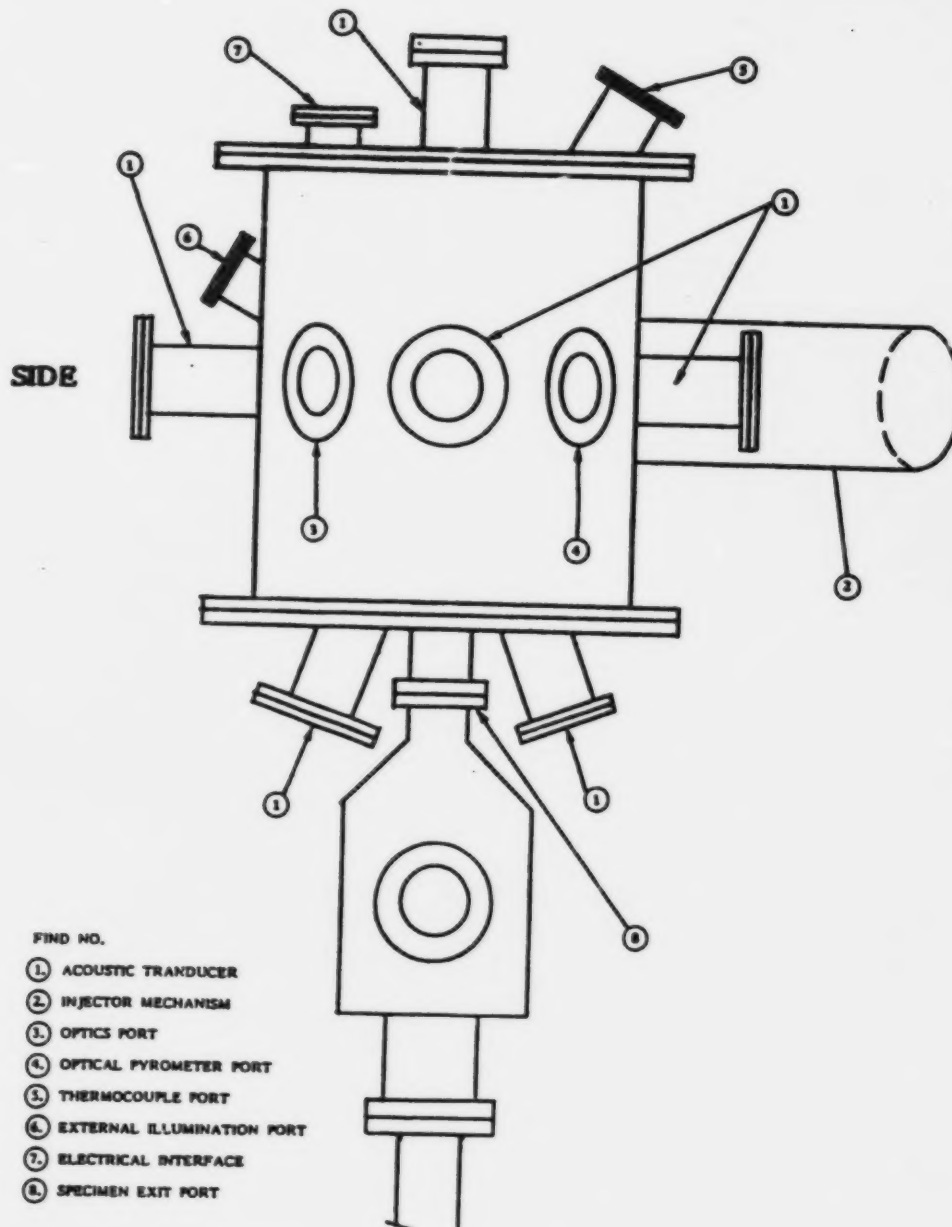


Fig. 7A LEVITATOR PROCESSING FACILITY (SIDE VIEW)

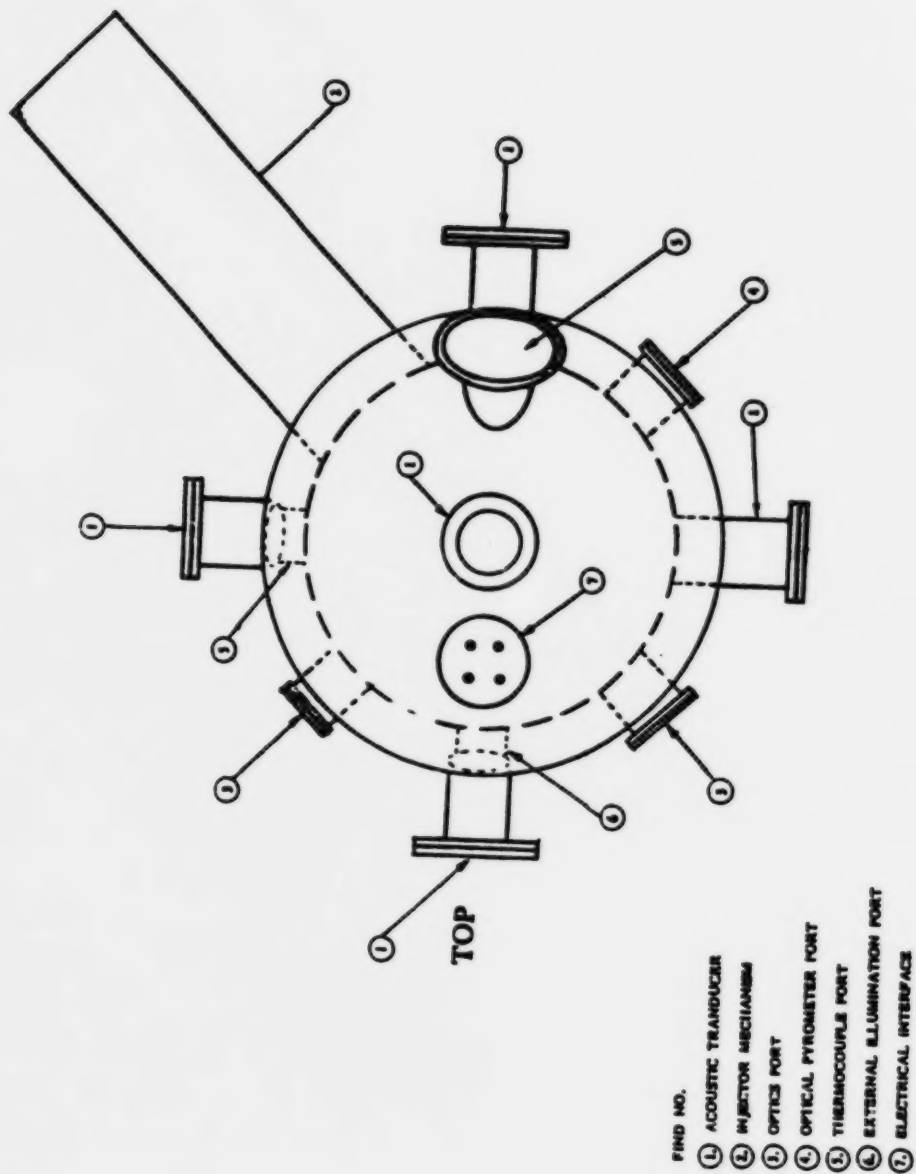


Fig. 7B LEVITATOR PROCESSING UNIT (TOP VIEW)

Other features of the major processing unit include a Specimen Handling Insertion and Retrieval System (SHIRS), a Gas Quench Cooling System, a separate cooling subsystem, and a temperature measurement and data acquisition system. The interdependence of these various supporting subsystems with the central assembly is shown in the block system diagram, Fig. 8.

5.2 System Functions

This apparatus is designed such that the furnace may be preheated to a desired temperature with the entire system filled with gas or gas mixtures appropriate for the experiment. A solid specimen can then be injected into the center of the furnace cavity. Acoustic fields produced by an array of 8 high frequency transducers is used to levitate the specimen without physical contact after it is released by the injector mechanism. The temperature profile for the processing of the specimen may be preset. The specimen, in general, will be heated, melted, and processed without physical contact or the need for a container.

The cooling rate may be determined by a programmed furnace temperature ramp down, or the furnace may be turned off and the cooling increased by the acoustic gas quench cooling system. This technique involves injecting a gentle flow of cool gas in the vicinity of the specimen while it is being positioned in the acoustic levitator.

Finally, a solid specimen may be removed from the furnace system by the SHIRS which uses a vacuum chuck. An alternate method, as already mentioned, which may be useful for liquid specimens, is to remove the acoustic fields and allow the specimen to drop through a hole in the bottom of the furnace. It can then be caught in a basket in a small chamber just below the furnace levitator

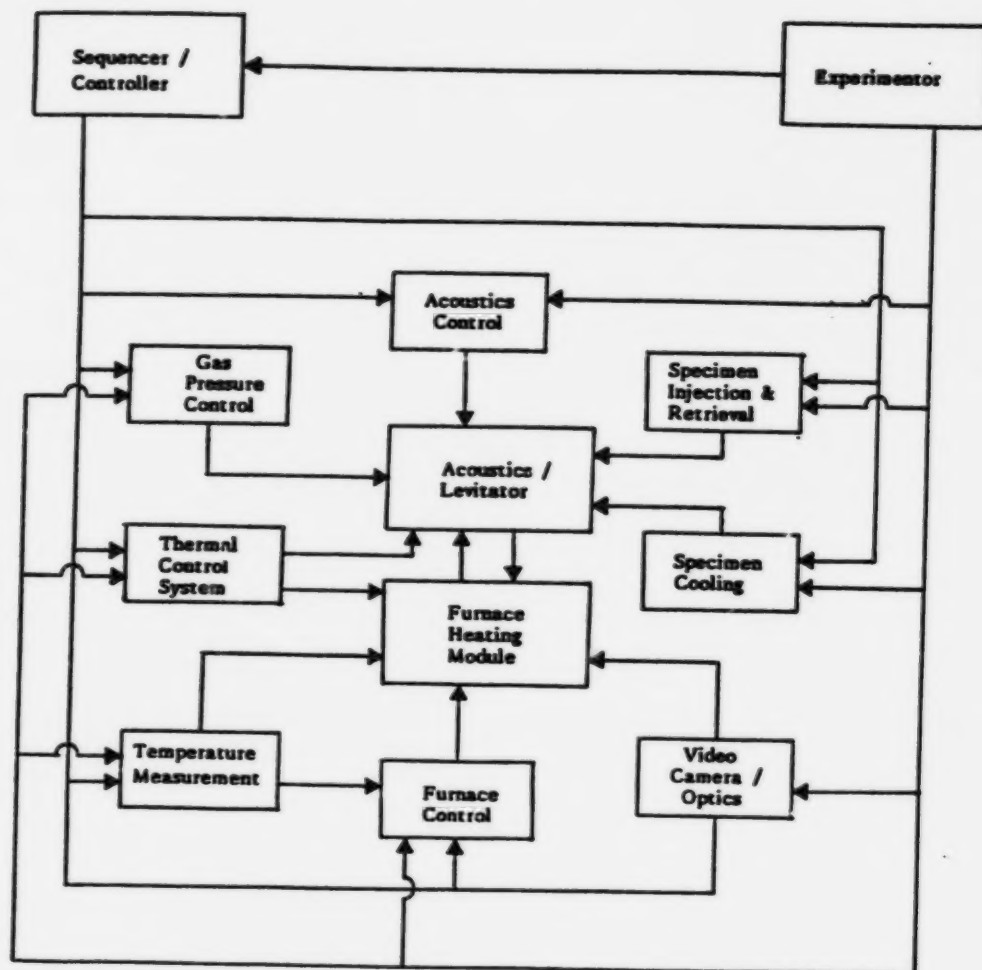


Fig. 8 HIGH PRESSURE LEVITATOR FUNCTIONAL BLOCK DIAGRAM

assembly, or allowed to free fall into a drop tube and then captured. This option may be of value in the study of rapid specimen cooling through the phase transition temperature.

During the containerless processing stages the specimen may be viewed optically through two orthogonal ports with external illumination being applied through a port in between those two. A specimen temperature may be obtained directly by optical pyrometry through a third, similar port and the furnace temperature and temperature profile may be measured by a set of thermocouples. After processing one specimen, additional specimens may be processed in a similar fashion. Note that the gating of the specimen insertion system allows specimens to be inserted without the necessity of depressurizing the entire chamber.

The controls for the pressure facility permit completely semi-automatic or complete manual operation of all functions. In the former case, furnace temperature control may be preprogrammed while certain subfunctions, primarily the injection of a specimen, need only be initiated by the operator. The insertion and release of the specimen into the acoustic field is then automatically executed.

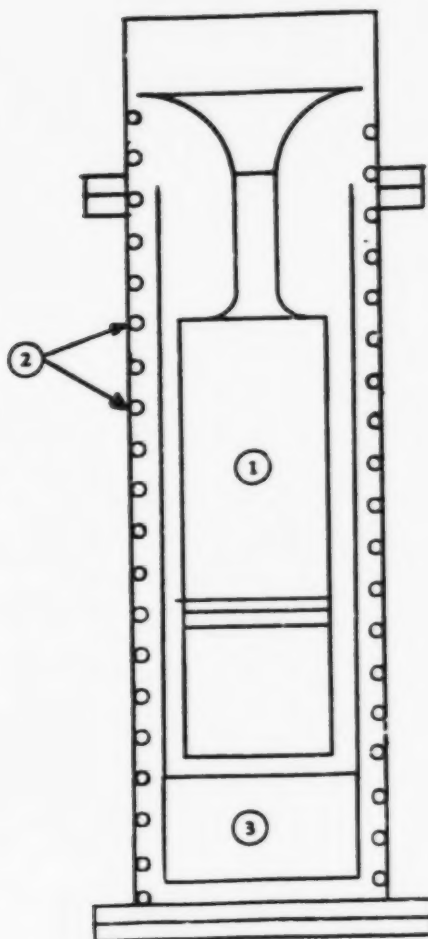
The details of the features and operations of the entire system are discussed by subsystem in the remainder of this section.

5.2.1 Acoustic Transducer Assembly

The acoustic transducer assemblies, as shown in Fig. 9, will consist of an acoustic driver mounted within a cooling jacket and pressure tight

cylinder which also serves as the mounting assembly. The acoustic transducer is a high efficiency design utilizing a piezoelectric drive motor coupled to a resonant transforming stub. This is then coupled to a flexing radiator which provides a large surface area vibrating at a large displacement. This produces a high intensity sound field with a narrowly focussed beam pattern, which is desirable for levitation purposes. Although the increased pressure reduces the fatigue rate of the transducer, the use of Titanium alloy in transducer construction is also desirable. Titanium increases the transducer life at high sound pressure levels as well as being very heat resistant. These transducers can produce SPL's in excess of 166 dB at 1 atmosphere, and substantially higher with increases in ambient pressure. A liquid coolant loop and a cooling fan are also shown in Fig. 9. This will serve to remove both the heat produced by the input power to the transducer as well as the heat conducted from the processing furnace. This coolant loop is part of the overall cooling system fluid loop. The sound source mounting tube, to which the cooling coil is mounted, provides a mounting flange for fastening to the main pressure vessel while providing a pressure seal.

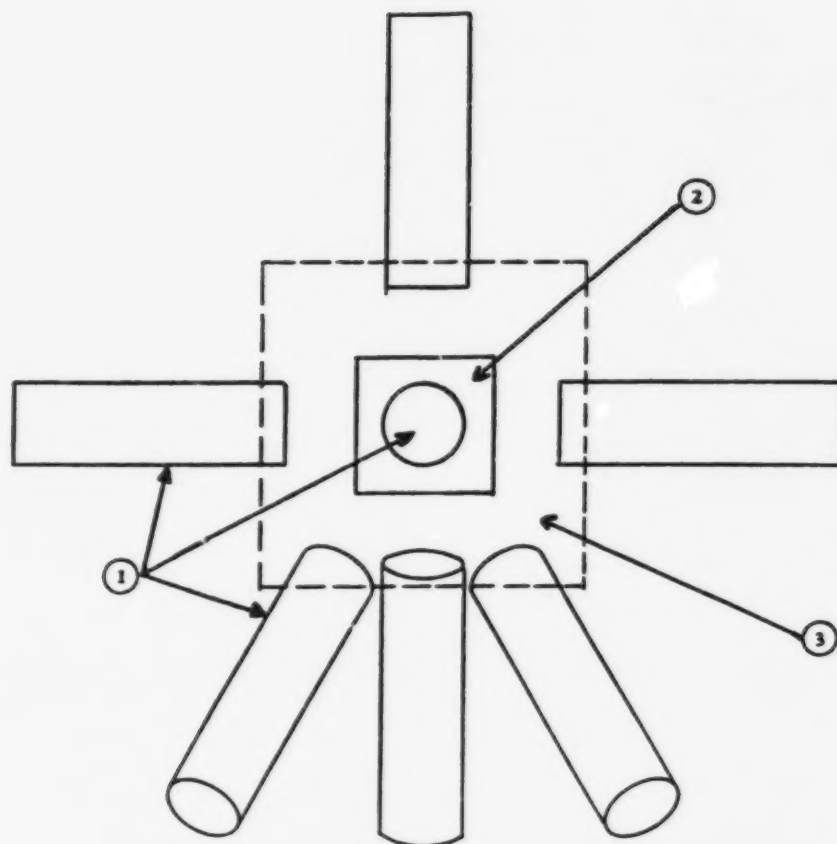
The specimen positioning in the proposed design will be provided by an array of eight of the transducers described. This conceptual design configuration is illustrated in Fig. 10. A cluster of three transducers at the bottom of the furnace will provide a very high intensity highly focussed beam pattern at the specimen. Very large positioning forces are provided in the



FIND NO.

- ①. ACOUSTIC TRANSDUCER
- ②. COOLANT TUBES
- ③. FAN

Fig. 9 ACOUSTIC TRANSDUCER ASSEMBLY



FIND NO.

- (1) ACOUSTIC TRANSDUCER
- (2) FURNACE CAVITY
- (3) FURNACE INSULATION

Fig. 10 ACOUSTIC TRANSDUCER ARRANGEMENT

axis normal to the force of gravity by the interference pattern produced by this cluster and the top transducer. The remaining four transducers, which are positioned around the circumference of the furnace at 90° intervals, will provide additional positioning forces in the radial directions.

5.2.2 Power Amplifier and Acoustic Controller

A block diagram of the Acoustic Control System is shown in Fig. 11. This is a typical configuration which would be reproduced for the number of sound sources that are used. The proposed design calls for eight.

The power amplifier and acoustic controllers used in this facility will be of an existing design which has been proven effective and reliable. The power amplifier, is designed specifically to drive the types of impedances encountered using the sound sources previously described. The acoustic controller circuit is a phase locked loop circuit which is capable of tracking the resonant frequency shift of a sound source over a wide range of frequencies. This has been specifically designed for this type of application, where significant transducer temperature rises are involved. This sound source heating, due to exposure to the furnace, causes resonant frequency shifts which must be tracked in a closed loop manner to maintain reliable performance.

5.2.3 Furnace Heater Module

The High Pressure Acoustic Levitator heating module concept is presented in Fig. 12, which shows a heated cavity approximately 14 cm in diameter, and 15 cm in height. The heaters shown are U-shaped elements of molybdenum dicilicide, such as KANTHAL Super ST 2-shank elements. With elements having a heated length of 125 mm and a diameter of 6 mm, the nominal power rating is 850 Watts per element, so that with 8 elements a total power

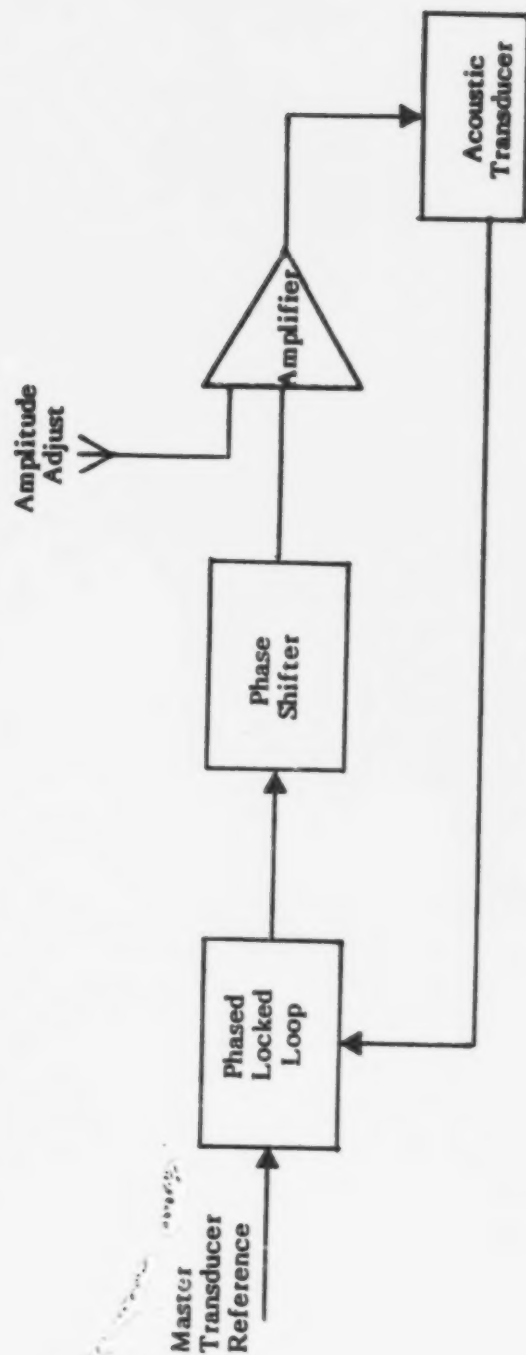
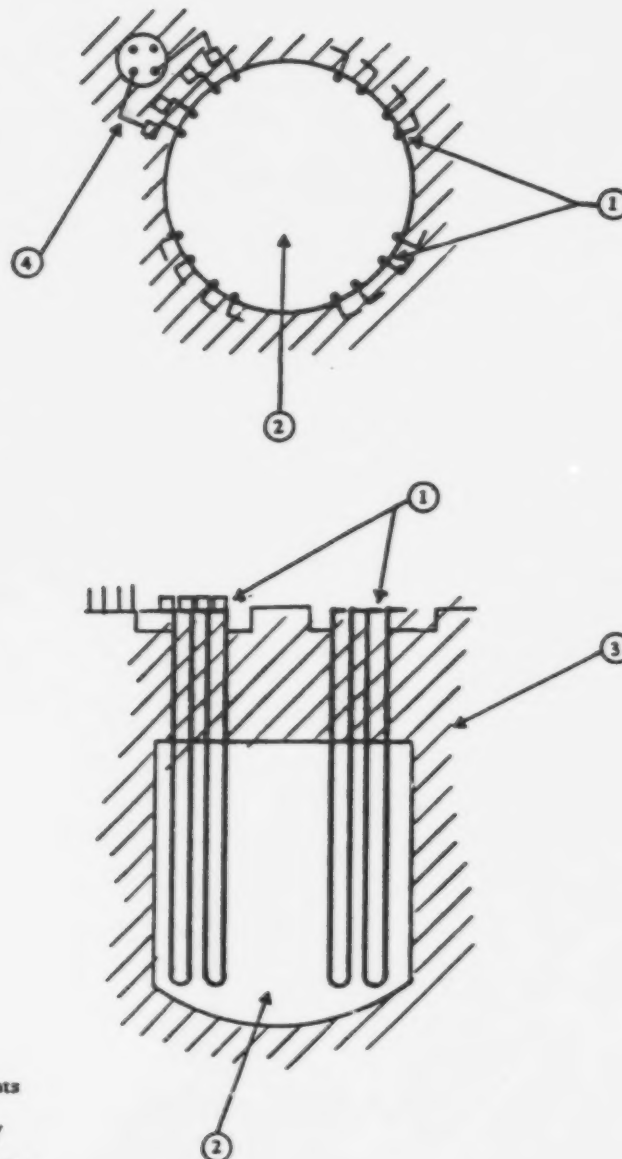


Fig. 11 ACOUSTIC CONTROL SYSTEM BLOCK DIAGRAM



FIND NO.

- ① Heater Elements
- ② Furnace Cavity
- ③ Furnace Insulation
- ④ Furnace Electrical Connect

Fig. 12 FURNACE HEATING MODULE

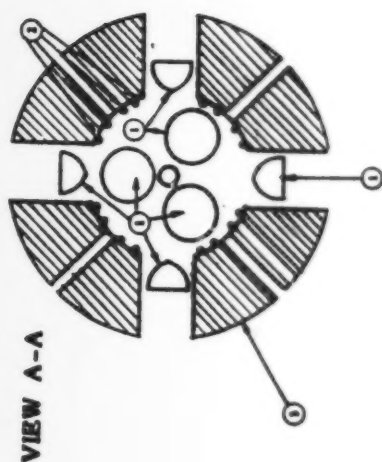
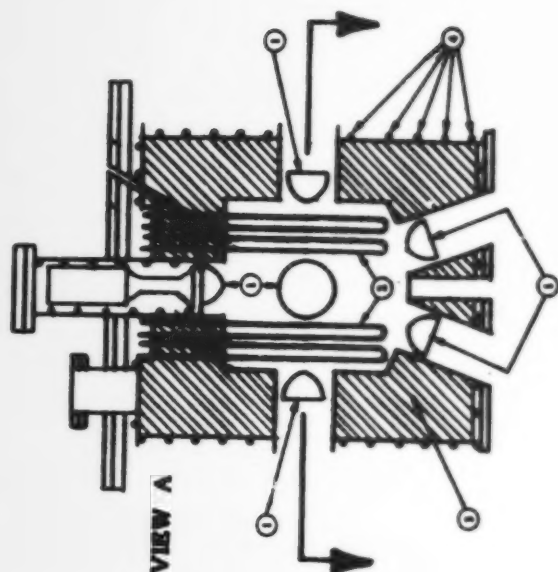
input would be 6.8 kW. The total estimated power requirement for a furnace of this heated volume, operating at one atmosphere pressure, lies between 3 and 4 kW at 1500° C. The element temperature would be 1650° C, safely below the maximum 1700° C as recommended by the manufacturer.

The spacing of the elements would be such that there is approximately a 14 mm interval between the elements in the region where there are optical or specimen injector ports into the processing cavity. A larger space, as shown in the Fig. 12, of approximately 50 mm is reserved for the entry ports for the four acoustic channels around the walls of the cavity.

5.2.4 Furnace Configuration

The furnace configuration consists of a hot wall, electrically heated furnace module, which uses four pairs of molybdenum dicilicide heating elements, as described in Sec. 3.2.3. Referring to Fig. 13, these elements are arranged so that there is sufficient space between each of the four sets to accommodate the acoustic ports for the four acoustic transducers arranged around the sides of the chamber. The furnace processing cavity is lined with alumina plates providing clean surfaces and good mechanical stability. The next layer of insulation is a high efficiency, low density fibrous alumina insulation. The outer layers would employ higher strength versions of a similar insulation.

In order to minimize heating loss through the ports there are insulating baffles, designated (1) in Fig. 13, in each of the acoustic channels. The other ports are kept as small in cross section at areas wherever possible to limit the radiated heat loss. To prevent convection driven gas through any of the ports, each port will be sealed completely, with optics ports utilizing high temperature VYCOR windows. The thermocouple probes enter



FIND NO.

- ① ACOUSTIC PORTS (INSULATING BAFFLES SHOWN)
- ② HEATING ELEMENTS
- ③ FURNACE INSULATION
- ④ COOLANT TUBES

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Fig. 13 FURNACE INTERIOR CUTAWAY

through two passages, one from the top plate and one from the backside. Outside of the furnace insulation there is a metal jacket which is water cooled and which will prevent the pressure vessel from reaching excessive temperatures.

The furnace assembly can be removed from the pressure vessel by unbolting the top plate and lifting the entire core out of the tank.

The pressure vessel was designed to be as small in diameter as possible in order to drop the overall weight and to keep the cost lower. The configuration would be of stainless steel with welded access flanges for the various ports. These flanges will be equipped with O-ring seals. Although the top and bottom plates are robust, they may require reinforcing gussets on the outside of the tank in order to provide a desirable margin of safety.

The pressurized volume is a cylinder of approximately 42 cm diameter and 52 cm in height. This gives a pressurized volume of about 70 liters, or approximately 2.5 cu. ft.

In the base of the tank, the specimen exit port is connected through a sliding gate valve (not shown in the diagram) to a pressurized receiving chamber and/or a pressurized drop tube.

5.2.5 Gas Quench System

In order to rapidly cool a specimen at a rate greater than that obtainable by the furnace cool down rate alone, a cool gas can be directed around the specimen. Fig. 14 shows a gas quench cooling probe which can be inserted into the region near the specimen and bathe the specimen with a smooth non-disruptive flow of gas. The flow rate of this cooling gas can be adjusted and monitored. In addition, the cooling gas being used does not have to be the same as the processing gas. The control for this subsystem is shown in the Gas Control Schematic shown in Fig. 16.

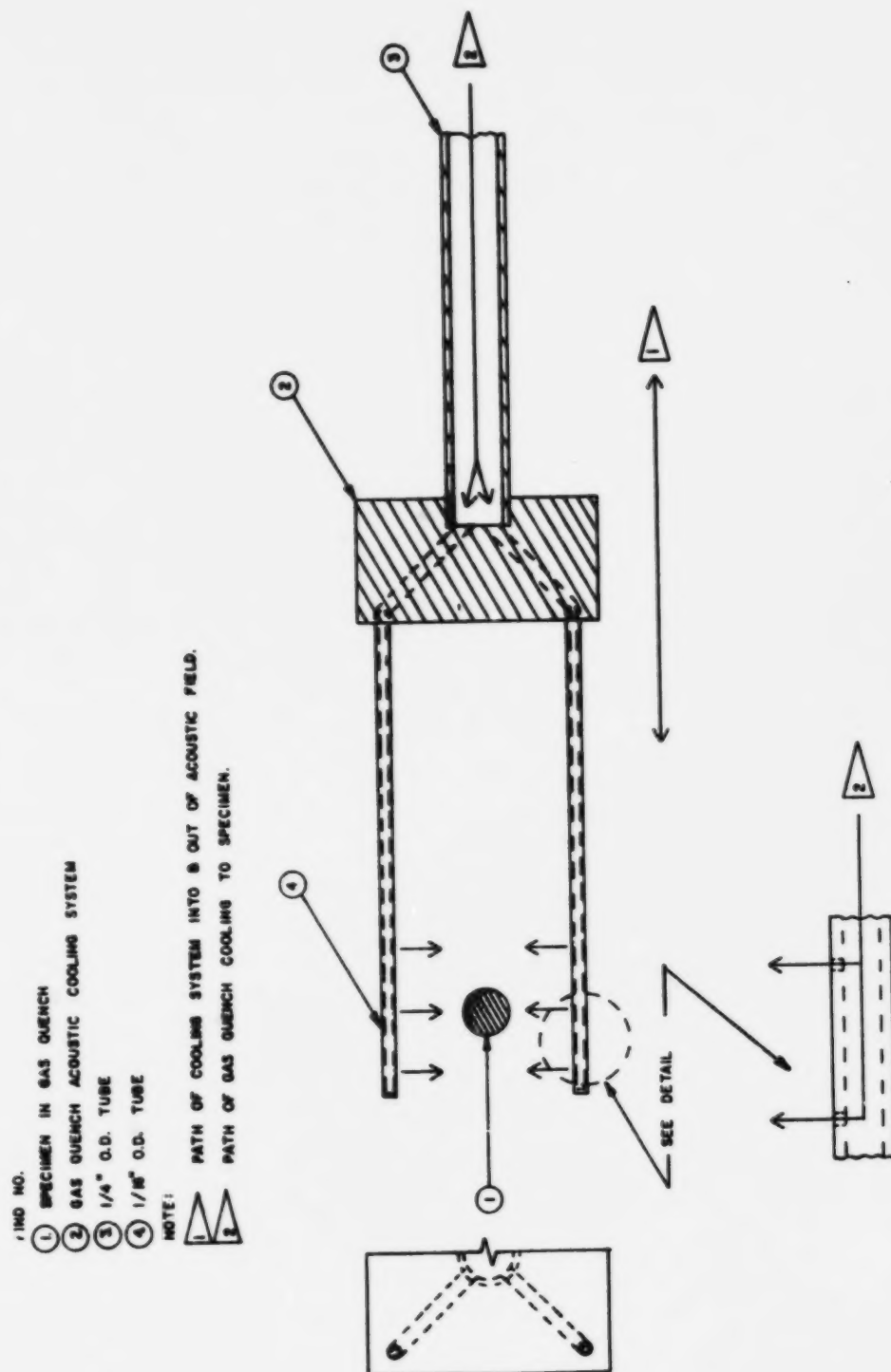


FIG. 14 GAS QUENCH ACOUSTIC COOLING SYSTEM PROBE

5.2.6 Specimen Handling System

The Specimen Handling Insertion and Retrieval System (SHIRS) will utilize a vacuum chuck device for holding the specimen while a linear traversing slide mechanism is used to insert and retrieve the specimen. Fig. 15 shows a lead-screw driven linear traversing slide mechanism which is motor-driven through a timing belt assembly. A long ceramic tube is shown mounted to the sliding carriage. The end of this tube serves as the vacuum chuck for specimen insertion. Specimens can be placed in a holder within the SHIRS through a sealed access port in the wall of the assembly. Once the specimen is acquired from the holding tray by the vacuum chuck, it can be inserted into the furnace through an access port which is sealed off by a remotely actuated gate valve.

In a typical specimen insertion sequence, the specimen would be placed in the holding tray of the SHIRS through the access port. This operation is done with the SHIRS Assembly vented to 1 atmosphere. Once the specimen is placed in the tray, suction to the vacuum chuck can be applied using an external vacuum pump, thus capturing the specimen. The access port will be closed, and the SHIRS Assembly can be pressurized to equal the pressure in the main processing vessel. With the pressure now equalized, the gate valve will be opened, exposing a port into the main processing vessel. The linear traversing mechanism can then insert the specimen into the processing chamber. Once the specimen is in the acoustic positioning field, the vacuum can be removed from the chuck, the specimen released, and the chuck retracted. The reverse process can be applied for specimen removal or else the specimen can be dropped out into the lower cooling chamber as was previously described in Section 3. The gas and vacuum control functions can be seen in the gas control system schematic in Fig. 16.

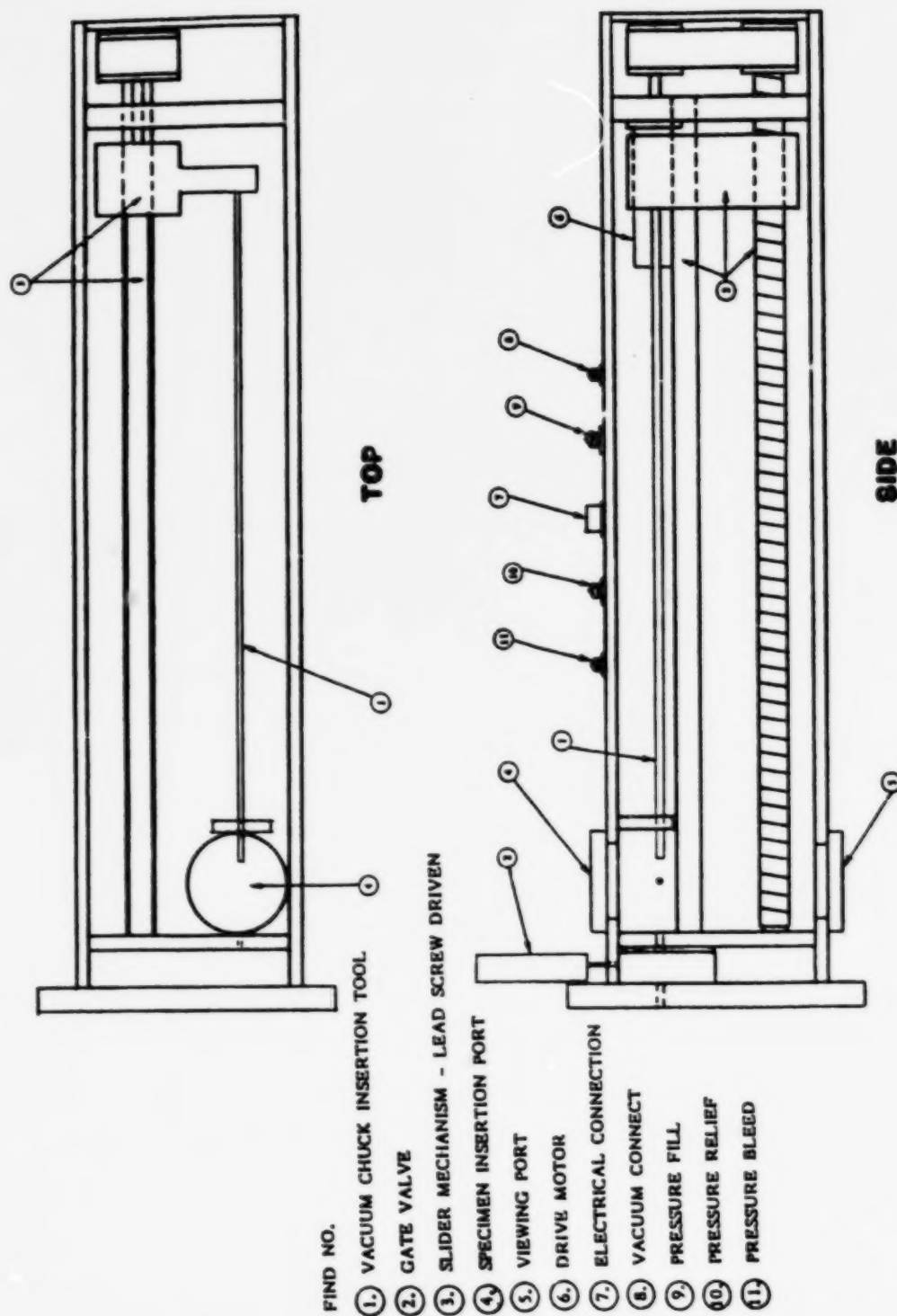


Fig. 15 SPECIMEN HANDLING INSERTION & RETRIEVAL SYSTEM

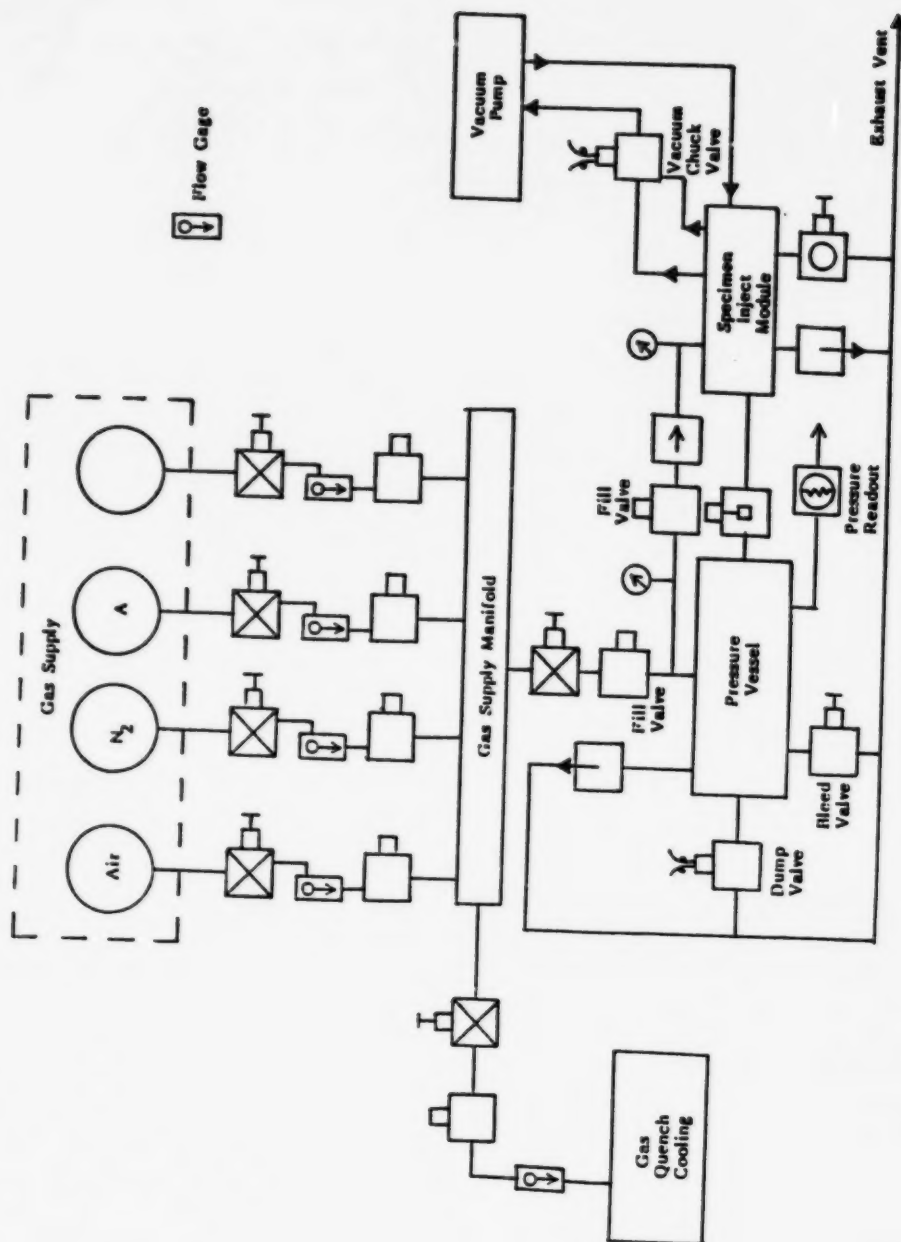


Fig. 16 GAS CONTROL SYSTEM

5.2.7 Gas Control System

The primary function of the gas supply system is to provide a pressurized atmosphere in which specimen positioning and processing can occur. A schematic diagram for a system which accomplishes this, as well as the other related functions, is shown in Fig. 16.

The main gas supply consists of a number of high pressure tanks, each containing a different gas. They are shown here as Air, Nitrogen, and Argon. The fourth container represents any mixture of gases that the user may require, assuming the gases are compatible with the system. Each gas has its own regulator, visual flow gauge, and valve, and are all terminated in a gas supply manifold. This will facilitate mixing of gases to produce a desired processing atmosphere.

The pressure vessel, or main processing vessel, is then pressurized by a single valve and pressure regulator. This valve, as well as several others in this schematic, is shown as a basic valve. This allows flexibility to operate them by hand or to make them remotely operated solenoids, depending on the final design. The pressure vessel is also equipped with a relief valve for safety reasons, a pressure dump valve for full de-pressurization, and a bleed valve which is necessary for regulating pressure as temperatures increase. These valves are all tied to an exhaust line which can be vented as the user requires.

A pressure transducer is also provided and the signal can be read out as well as placed on the computer data bus for monitoring or control purposes.

Additional functions of the gas control system include controls for gas quench cooling and pressurization of the Specimen Handling Insertion and Retrieval System.

The Gas Quench Cooling System is shown as having its own regulator, valve, and visual flow gauge, so that by tying it into a separate gas supply the quench cooling gas need not be the same as the processing gas. Again, this valve could be remotely actuated if specified in the final design.

The Specimen Handling Injection and Retrieval System pressure can be equalized with the pressure in the main processing vessel with one valve. A check valve is included in the fill line for the SHIRS to prevent gas from returning to the main vessel in the event of a reverse pressure differential. A pressure gauge is provided on this module also. The SHIRS also has a relief valve and a bleed valve, both of which are vented to the main exhaust vent. The operation of SHIRS, including the vacuum chuck operation, which is also shown in this schematic, is described in further detail in Section 3.2.6 of this report.

5.2.8 Furnace Power Subsystem

The Furnace Power Subsystem, which is shown in Fig. 17, will utilize a PID controller to provide maximum flexibility in temperature profiles, including controlled cooling and heat up rates. Platinum Rhodium thermocouples will provide the temperature feedback information to the PID controller. By allowing the user the flexibility of multiple thermocouples in various locations, the user can select any one of the six thermocouples to be used for furnace temperature control.

The high powers that are required to heat a furnace under pressure will require the use of a 240 V 3 ϕ supply. Input powers in excess of 5 Kw can be expected at the higher temperatures at elevated pressures. The power vs. pressure curves shown in Fig. 1 are indicative of the power requirements, although the new designs presented should provide some improvements in efficiency.

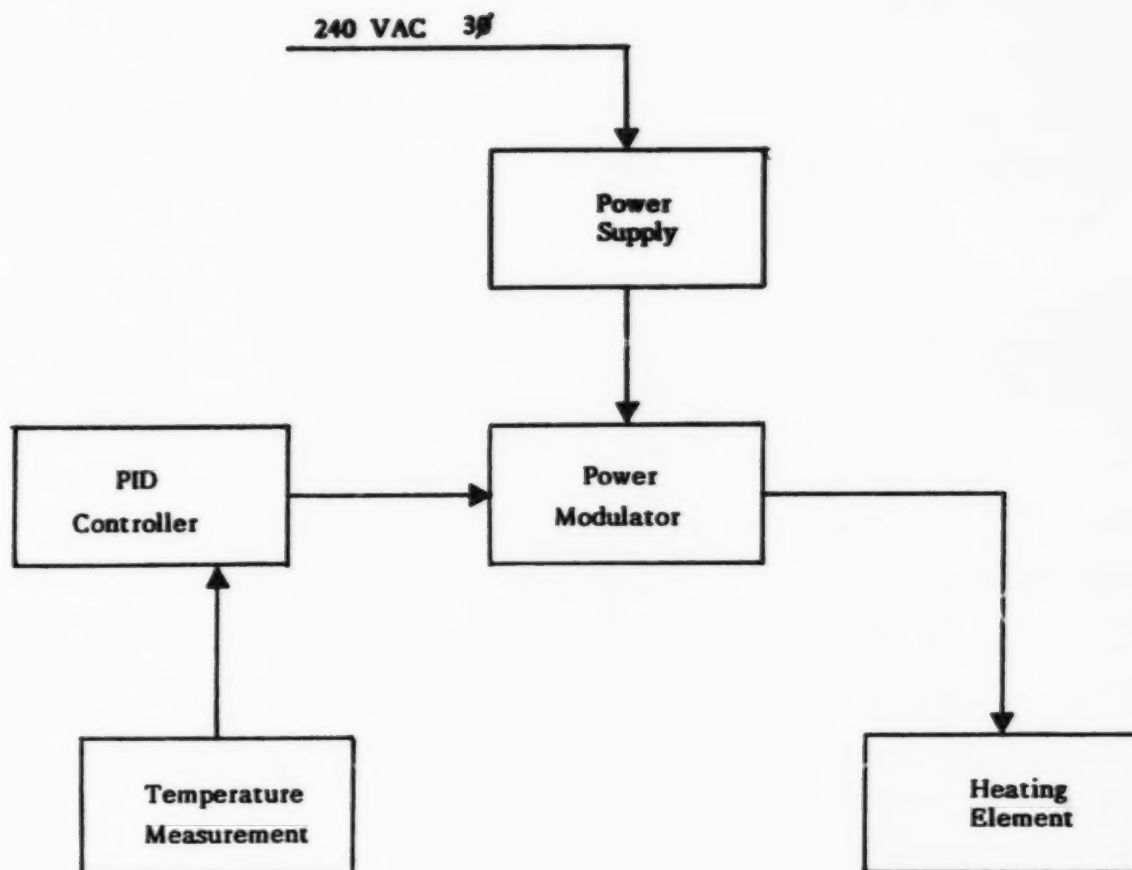


Fig. 17 FURNACE POWER SUBSYSTEM

Due to the extremely low impedance of the heating elements being used, conditioning of the 240 V AC is required to properly drive them. Following the power supply conditioning, a power modulator, and a current regulator, is utilized in conjunction with the PID controller to provide the power drive to the heating elements.

5.2.9 Cooling System

Maintaining proper thermal operating conditions for all pertinent subassemblies will be accomplished through a system coolant loop, Fig. 18. The temperature of each of the acoustic transducers must be maintained at an appropriate level to insure optimum performance necessary for levitation. Referring to Fig. 9 and Fig. 13, these thermal requirements are met by means of a cooling coil jacket around each transducer. An analog signal is directed to the data acquisition system providing the current temperature of that transducer. Flow through the cooling coil may then be regulated accordingly to maintain proper operating temperature. Similarly, a cooling coil surrounds the outer insulation of the furnace heater module. Temperature limits are necessary here to avoid high surface temperatures for the pressure vessel and over-temperatures of associated components on the processing chamber. Coolant within the system will be H_2O with an inlet temperature of 4 to 30° C and a flow of 720 liters/hr.

5.2.10 Temperature Measurement System

The Temperature Measurement System, as shown in Fig. 19, will utilize a number of Platinum Rhodium thermocouples as its basis. Standard thermocouple reference junction technology will be applied with a dedicated, isolated power supply used to provide maximum accuracy and noise immunity. The signal conditioning circuitry will provide conditioning both for feedback to the PID

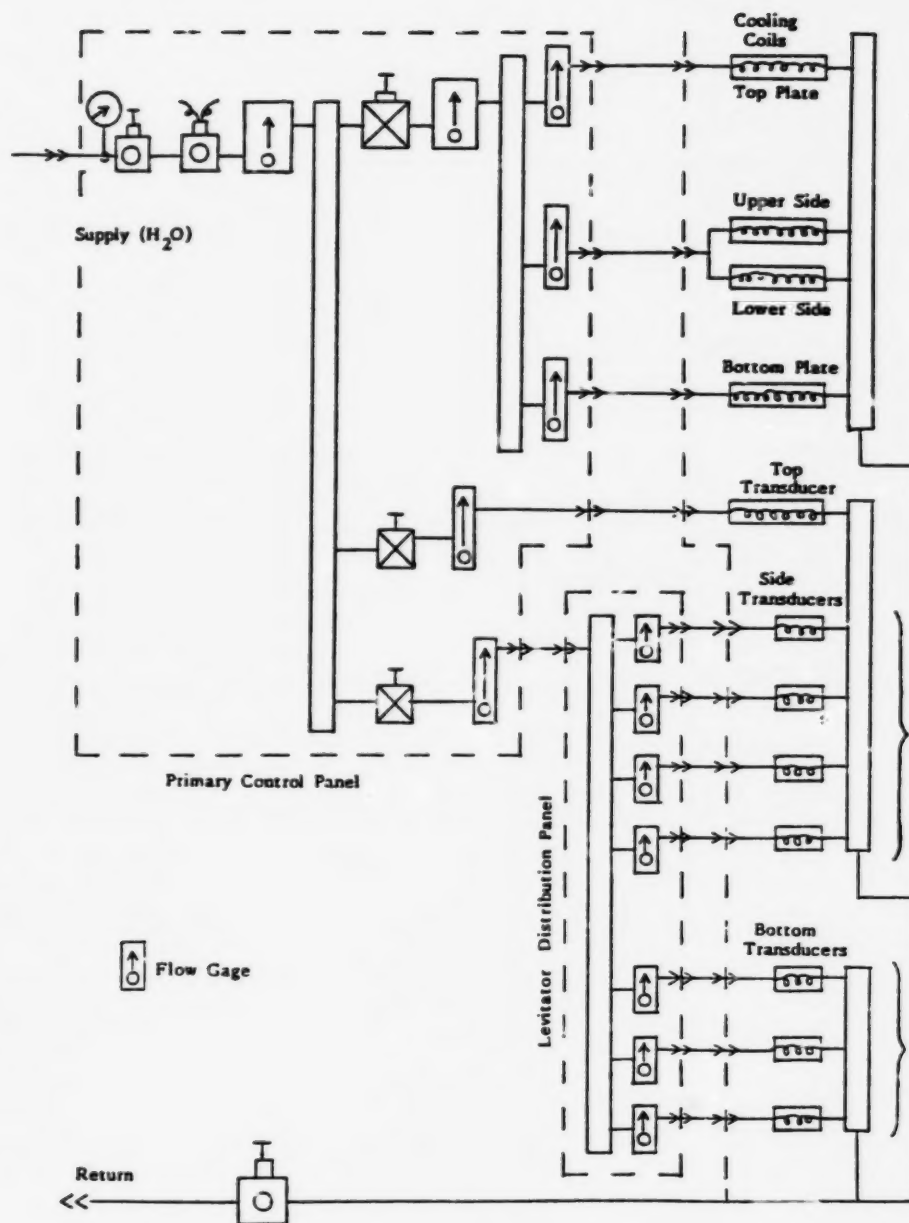


Fig. 18 LEVITATOR COOLING SYSTEM

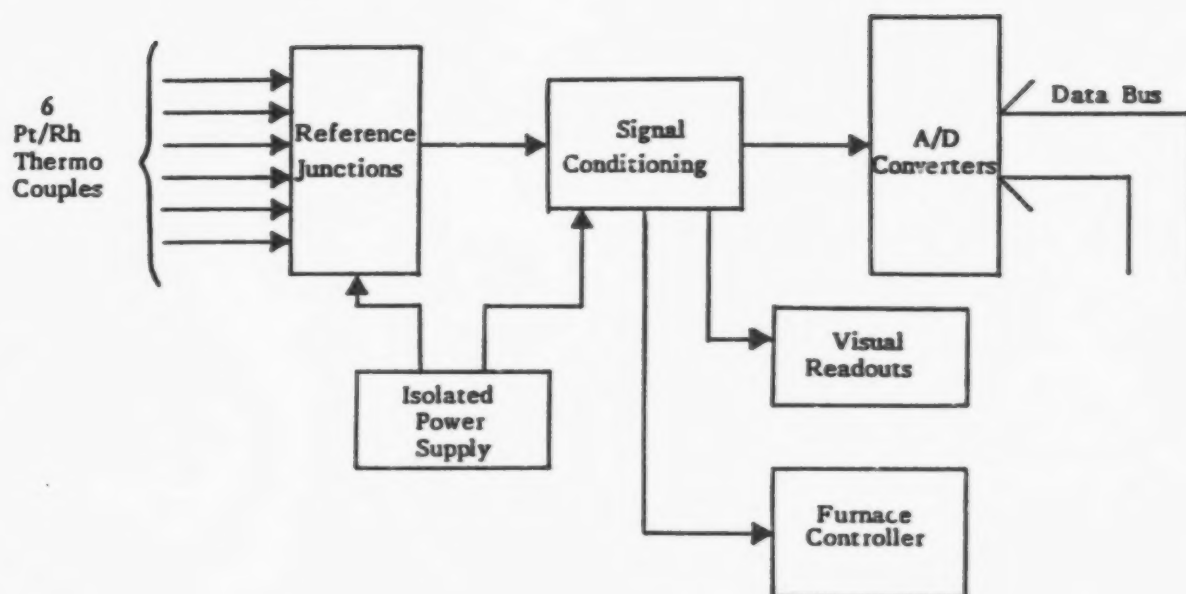


Fig. 19 TEMPERATURE MEASUREMENT SYSTEM

controller as well as temperature readout. The temperature signals, in addition to being available for direct readout, will also be passed through an A/D converter and placed on the computer data bus. The data can then be stored and/or used for additional control purposes.

In addition, an infra-red transmitting optical window will be provided on the main processing chamber in order to facilitate the use of user supplied optical pyrometry.

5.2.11 Levitator Control System

The Levitator Control System block diagram is shown in Fig. 20. The control functions originate at the computer system which includes the computer, keyboard, monitor, printer, and plotter. With these necessary peripherals complete experiment analysis and evaluation can be performed. All control and acquisition functions are then interfaced into the computer data bus or appropriate port for analysis. Subsystems under control include the acoustics, furnace temperature, specimen inject and release, specimen cooling system, gas pressure, system temperature, and video recording of the processing run.

The acoustics control for the system is accomplished through control of each of the acoustic power amps. Each of the acoustic transducers can then be evaluated through the acquisition of data including transducer amplitude, frequency, temperatures, drive voltage and current.

The furnace temperature desired for a processing run will be maintained through computer commands to the PID furnace power controller, in addition to a feedback thermocouple signal which is an input to the PID controller. In addition, up to six thermocouples will indicate overall furnace temperature with furnace input power also being recorded.

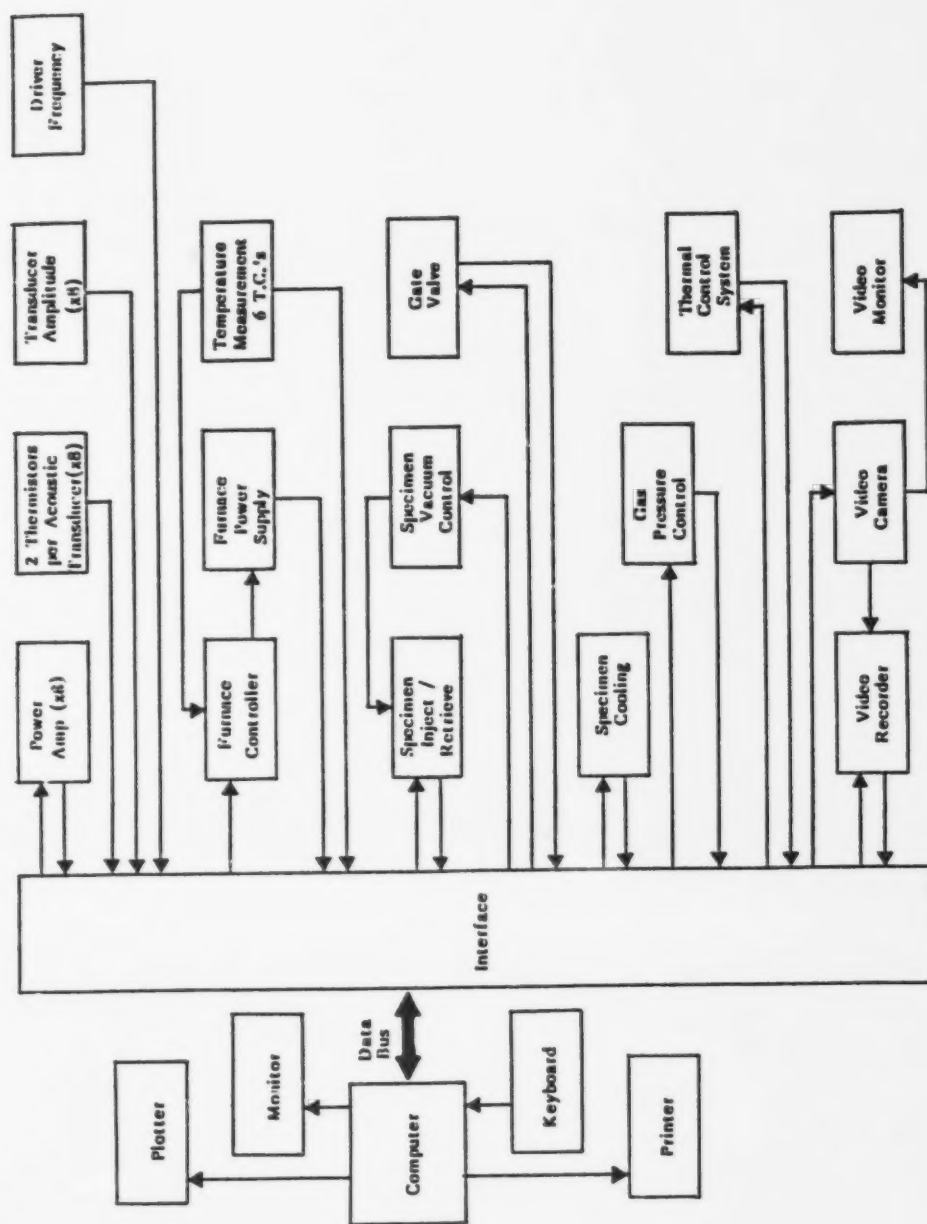


Fig. 20 DATA ACQUISITION & CONTROL BLOCK DIAGRAM

The specimen inject-retrieve sequence (see Section 4.7) will be accomplished by controlling the pressurization of the injection-retrieval assembly, the vacuum status of the vacuum insertion and retrieval tool, opening and closing of the gate valve, and translation of the vacuum chuck into and out of the furnace cavity. The status of the above mentioned operations will be monitored through readbacks as presented in the block diagram, Fig. 20.

Specimen cooling, system gas pressure, and thermal control of the processor also will be monitored via the computer system. Again, readback signals will provide information with regard to the status of each of these operations. Finally, control of the video recording operations will be useful to the success of the experiments performed. Recording analog data and processing events into the video tape will be helpful in the analysis of a given processing run.

6. SUMMARY OF RESULTS

The results of this study, which was to determine the feasibility of fabricating a high pressure acoustic levitator for containerless processing of materials in the 1-g environment of earth, have been presented in this final report, dated October 26, 1987. The use of increased gas pressure has been shown to produce higher sound pressure levels (SPL's) while reducing the harmonics produced by the acoustic source. These acoustic enhancements have provided an improvement in the capabilities of acoustic levitation in 1-g. Although the absolute maximum capabilities for the containerless processing of materials in 1-g using acoustic levitation have not been determined, the processing capabilities reported here are directly limited by the design of the Intersonics Medium Pressure Acoustic Levitator (MPAL) used for this study. Data collected thus far from experiments with the MPAL indicate that sufficient acoustic intensities can be obtained so that a specimen of density 5 g/cm^3 could be levitated and processed (without a container) at temperatures of 1500°C . Bench marks were in fact established that included levitation of specimens of density 4 g/cm^3 at 1050°C and levitation of density $.53 \text{ g/cm}^3$ at 1350°C . However, poor isothermality, large gravitation-induced convection, and acoustic streaming encountered in these experiments utilizing the MPAL limited these results. It is therefore recommended that a working engineering model be developed as a prototype of the proposed design presented in this report in order to establish the maximum temperatures and densities that can be successfully levitated.

6. SUMMARY OF RESULTS

6.1 General Specifications for HPAL

Max. furnace temperature	1500°C
Typical levitation time	.5 hour
Specimen density	< 5 gm/cm ³
Total system pressure	1 to 20 atm
Furnace cavity:	
Approx. height	15 cm
Approx. diameter	14 cm (irregular)
Wall material	Alumina
Specimen handling:	
Loading	Air lock on port
Holding	Vacuum chuck
Injection	Linear translation of injection tube
Specimen shape	Approximately spherical
Specimen surface	Smooth for vac. chuck
Specimen size	2 - 5 mm diameter
Sample cooling	Acoustic gas quench
Cooling rate	0 to 100° C/min or more
Gases used:	Air, Argon, N ₂ or mixes
Oxygen limits	≤ 0.21 bar partial pressure

System power requirements:

Furnace	3 ϕ AC
Current	30 Amps peak
Control	1 ϕ 120 VAC
Current	< 20 Amps
System Cooling	Water
Inlet temperature	< 30° C
Flow rate	< 720 l/hr

Temperature measurement:

Sensors	Thermocouple
Type	Ansi Type S
Number	Up to 6
Readout	Via data acquisition
Supplementary system	Optical pyrometer
Access	1 quartz window port.

Access ports:

Optical/(or spares)	8 total
Pyrometer	2 - at 90° apart on side
External illumination	1 - on side wall
Thermocouple/(or spares)	1 - between optical
Injector	2 - on side & top
Specimen exit port	1 - on side
	1 - on bottom plate

Control system:

Modes	Manual, semi-automatic
Controller	Computer
Interface	RS-232 serial or other

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16. Abstract This is the final report for the program entitled "Program for the Feasibility of Developing a High Pressure Acoustic Levitator." It includes work performed during the period from February 15, 1987 to October 26, 1987. The program was conducted for the National Aeronautics and Space Administration (NASA) under contract number NAS3-25115. The objective of the study was to determine the feasibility of fabricating a high pressure acoustic levitator (HPAL). The HPAL would be used for containerless processing of materials in the 1-g environment of earth. Results show that the use of increased gas pressure produces higher sound pressure levels (SPL's). The harmonics produced by the acoustic source are also reduced. This provides an improvement in the capabilities of acoustic levitation in 1-g. The reported processing capabilities are directly limited by the design of the Medium Pressure Acoustic Levitator (MPAL) used for this study. Data shows that sufficient acoustic intensities can be obtained to levitate and process a specimen of density 5 g/cm³ at 1500 °C. However, it is recommended that a working engineering model of the HPAL be developed. The model would be used to establish the maximum operating parameters of furnace temperature and sample density.					
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